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October 3, 1996

Dr. Michael VanWoert
ONR Code 322HL
Ballston Tower One
800 North Quincy Street
Arlington, VA 22217

Dear Mike:

Enclosed is the final report for ONR Grant N00014-90-J-1359. Funds for this project were awarded over a six year period through a series of renewals. The initial grant was entitled "Investigation of the Arctic Internal Wave Field" and was awarded for the period 1 Jan 1990 to 31 December 1992. This grant was renewed under the same title for the period 1 Jan 1993 - 31 Dec 1994. The scientific direction of the project shifted when the grant was renewed under the title "Small-scale processes in the Arctic Ocean and Sub-Arctic Seas" for the period 1 Jan 1994 - 31 Dec 1995. A no-cost extension was requested for this grant, extending the termination date until 30 September 1996.

Please let me know if you need any other information.

Sincerely,

A. Plueddemann

Dr. Albert J. Plueddemann
Department of Physical Oceanography
Woods Hole Oceanographic Institution
Woods Hole, MA 02543-1541

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Small-scale processes in the Arctic Ocean and Sub-Arctic Seas

FINAL REPORT

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ONR Grant N00014-90-J-1359
01 Jan 1990 – 30 Sep 1996

Background

This project involved two distinct scientific investigations. First, the characteristics of the internal wave field were examined at several locations in the Arctic Ocean. The objectives of this work were to determine the spectral shape and energy level of the Arctic internal wave field and to assess the relative importance of ice cover, bottom topography, and tides in the internal wave energy balance. Data sources for the investigation included the ice camp manned during the Cooperative Eastern Arctic Experiment (CEAREX) and an Arctic Environmental Drifting Buoy (AEDB) developed by S. Honjo at the Woods Hole Oceanographic Institution (Honjo *et al.*, 1990).

The second investigation focussed on the properties of the Barents Sea Polar Front and the fate of Atlantic Water found in the frontal region. The principal objectives of this work were to determine the dynamics of frontogenesis and the reasons for topographic control of the frontal location. The primary data source for this work was the 1992 Barents Sea Polar Front Experiment. Historical hydrographic data from the National Ocean Data Center (NODC) were also used.

Results: Arctic Internal Waves

The unprecedented sub-surface velocity record from the AEDB as it drifted from the Nansen Basin, over the Yermak Plateau, and into the Greenland Sea provided new insights into the high-latitude internal wave field. Plueddemann (1992) showed that the wave field over the Yermak Plateau was dominated by near-inertial wave groups generated at or near the bottom and propagating upwards. The energy level and spectral slope in the internal wave band over the ice-covered plateau were similar to those expected for mid-latitudes, and represented a jump in energy of about a factor of 2.5 from the nearby Nansen Basin. The magnitudes of the observed upward energy fluxes were as large as the downward fluxes typically found at mid-latitude. Thus, it appears that considering the nature of the high-latitude internal wave spectrum to

be governed by the properties of the ice cover, or the distance into the pack ice, is insufficient since strong, bottom sources of internal waves may be present in regions with relatively shallow, variable topography.

Interaction of the strong barotropic tide with bottom topography was considered to be the most likely source for the upward-propagating near-inertial waves over the plateau. Enhancement of the diurnal tide in this region had been known for some time, and it had been speculated that this was the result of a resonant topographic wave. The availability of new data allowed the first detailed regional examination of tidal variability. Observations from CEAREX, the AEDB, the Marginal Ice Zone Experiment (MIZEX), the Fram ice camps, and several moorings were reviewed by Padman *et al.* (1992). This work lead to the conclusion that enhanced diurnal tides near the plateau are the result of non-resonant topographic shelf waves generated on the eastern side, but unable to propagate around the entire plateau perimeter. It was also determined that the strong tide significantly influences the hydrography and circulation of the plateau region.

Results: Barents Sea Polar Front

Topographic control of the Barents Sea Polar Front along the southeast slope of Spitsbergen Bank has been recognized for some time, but a dynamical mechanism was lacking. The field study described by Parsons *et al.* (1996) provided the first detailed description of the front in a region of known topographic influence. Interestingly, a persistent westward flow of Atlantic Water was seen south of the front, whereas most previous results (using the geostrophic method) suggested a flow to the east or northeast. A dynamical explanation was provided by the modeling study of Gawarkiewicz and Plueddemann (1995). This work showed that the Polar Front can be considered the northern boundary of a topographically trapped, barotropic flow of Atlantic Water which enters the Barents Sea from the southwest and bifurcates at the sill between Nordkapp Bank and Sentral Bank. According to this hypothesis, the location of the front (at about 250 m depth, offshore of the shelf break) is set by the sill depth some 600 km upstream. A related result is that a large fraction of Atlantic Water entering from the Norwegian Atlantic Current is re-circulated within the trough and exits flowing westward south of Bear Island.

Hydrographic data from the 1992 Polar Front experiment were consistent with the topographic control theory of Gawarkiewicz and Plueddemann, but the field data were limited in extent and observations were made for only 20 days. As a first attempt to assess the regional applicability of the theory, historical hydrographic data in the western Barents Sea were re-examined by graduate student Carolyn Harris (Harris, 1996; Harris *et al.*, 1996). The analysis confirmed that the regional hydrography is consistent with topographic control of Atlantic Water inflow, and thus of the Polar Front. However, significant seasonal variability in water properties was seen near the surface, indicative of significant shelf-basin exchange. The dynamics of this exchange remain a subject for future study. Work to date indicates that dense water may

form south of the front due to a combination of freshening from sea-ice meltwater in the summer and convection due to surface cooling in the fall and winter. A revised seasonal cycle of water mass modification was developed to reflect this scenario.

Ancillary Activities

In addition to the two principal scientific thrusts, a variety of ancillary activities were undertaken. These are described briefly below.

Experience with the AEDB showed the value of Acoustic Doppler Current Profiler (ADCP) records from an Arctic drifting buoy. Adding telemetry capability to obtain the ADCP data in near real-time was appealing, but the ADCP data rate greatly exceeded the throughput of the Argos satellite system. To address this problem, a data processing module was developed for the ADCP (Plueddemann *et al.*, 1992) and successfully used to obtain 23 months of telemetered data from a second-generation Arctic drifting buoy (Singer *et al.*, 1992; Krishfield *et al.*, 1993).

The shipboard ADCP record from the Barents Sea Polar Front Experiment was not immediately useful for interpretation due to aliasing of the strong tidal signal on the Spitsbergen Shelf. Harris *et al.* (1995) extended and applied an existing tidal analysis technique to successfully remove tidal contamination from the shipboard ADCP data. The resulting "mean" velocity field from the frontal survey was a critical element in understanding the local circulation in the studies of Gawarkiewicz and Plueddemann (1995) and Parsons *et al.* (1996).

An ADCP was deployed in support of the ICESHELF–94 ice camp in the Lincoln Sea. The ADCP provided detailed information about tidal and internal wave variability in the upper 150 m of the water column. A technical report (Plueddemann and Galbraith, 1995) documents the results and includes a comparison of the ADCP to an InterOcean S-4 current meter also deployed at the site.

Highlights of the work on Arctic internal waves and the Barents Sea Polar Front were published in *Oceanus*, a general interest science magazine published by the Woods Hole Oceanographic Institution (Plueddemann, 1994; Gawarkiewicz and Plueddemann, 1994).

Collaborative work began with K. Sabinin of the Andreyev Acoustics Institute in Moscow. The relationship between near-inertial waves and the low-frequency vorticity field over the Yermak Plateau is being investigated using data from the AEDB. Characteristics of internal waves in the northeast Barents Sea are being studied using data from distributed temperature sensors deployed at Russian ice camps.

Publications supported by ONR N00014-90-J-1359

1. Refereed Publications

Gawarkiewicz, G., and A. J. Plueddemann, 1995. Topographic control of thermohaline frontal structure in the Barents Sea Polar Front. *J. Geophys. Res.*, **100**(C3), 4509–4524.

Harris, C. L., A. J. Plueddemann and G. G. Gawarkiewicz. Water mass distribution and polar front structure in the western Barents Sea. *J. Geophys. Res.*, submitted.

Lynch, J. F., G. Jin, R. Pawlowicz, D. Ray, A. J. Plueddemann, C.-S. Chiu, J. H. Miller, R. H. Bourke, A. R. Parsons, and R. Muench, 1996. Acoustic traveltime perturbations due to shallow water internal waves and internal tides in the Barents Sea Polar Front: Theory and experiment. *J. Acous. Soc. Am.*, **99**(2), 803–821.

Padman, L., A. J. Plueddemann, R. D. Muench, and R. Pinkel, 1992. Diurnal tides near the Yermak Plateau. *J. Geophys. Res.*, **97**(C8), 12,639–12,652.

Parsons, A. R., R. H. Bourke, R. D. Muench, C. S. Chiu, J. F. Lynch, J. H. Miller, A. J. Plueddemann, and R. Pawlowicz, 1996. The Barents Sea Polar Front in summer. *J. Geophys. Res.*, **101**(C6), 14,201–14,221.

Plueddemann, A. J., 1992. Internal wave observations from the Arctic Environmental Drifting Buoy. *J. Geophys. Res.*, **97**(C8), 12,619–12,638.

2. Technical Reports, and Non-refereed Publications

Gawarkiewicz, G. and A. J. Plueddemann, 1994. Where the Arctic meets the North Atlantic: Exploring the Barents Sea Polar Front. *Oceanus*, **37**(2), 17–19.

Harris, C. L., 1996. Water mass distribution and polar front structure in the southwestern Barents Sea. *M.S. Thesis*, MIT/WHOI Joint Program in Physical Oceanography, 106pp.

Harris, C. L., A. J. Plueddemann, R. H. Bourke, M. D. Stone and R. A. Pawlowicz, 1995. Collection and processing of shipboard ADCP velocities from the Barents Sea Polar Front Experiment. *Woods Hole Oceanogr. Inst. Tech. Rep.*, WHOI–95–03, 71 pp.

Honjo, S., R. Krishfield and A. Plueddemann. 1990. The Arctic Environmental Drifting Buoy (AEDB): Report of field operations and results. *Woods Hole Oceanogr. Inst. Tech. Rep.*, WHOI–90–02, 128 pp.

Krishfield, R. K. Doherty and S. Honjo, 1993. Ice-Ocean Environmental Buoys (IOEB): Technology and Development in 1991–1992. *Woods Hole Oceanogr. Inst. Tech. Rep.*, WHOI–93–45. 138 pp.

Plueddemann. A. J., 1994. A glimpse beneath the ice: Internal wave observations from a drifting buoy in the Arctic Ocean. *Oceanus*, **37**(2), 24–26.

Plueddemann. A. J. and N. R. Galbraith. 1995. ADCP Measurements from the ICESHELF 94 Experiment. *Woods Hole Oceanogr. Inst. Tech. Rep.*, WHOI–95–11. 85 pp.

Plueddemann. A. J., A. L. Oien, R. C. Singer and S. P. Smith, 1992. A data processing module for acoustic Doppler current meters. *Woods Hole Oceanogr. Inst. Tech. Rep.*, WHOI–92–05. 64 pp.

Singer, R. C. . A. J. Plueddemann, A. L. Oien. and S. P. Smith, 1992. In-situ processing of ADCM data for real-time telemetry. *Proc. Oceans '92*, IEEE, New York. 632–636.